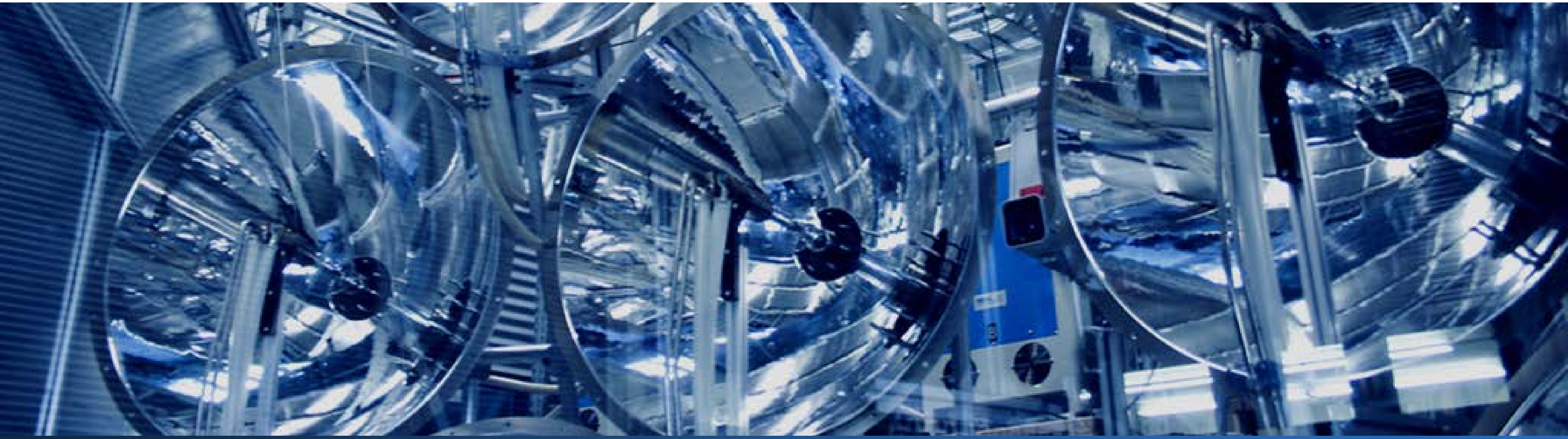
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Professorship of Renewable Energy Carriers
Institute of Energy Technology

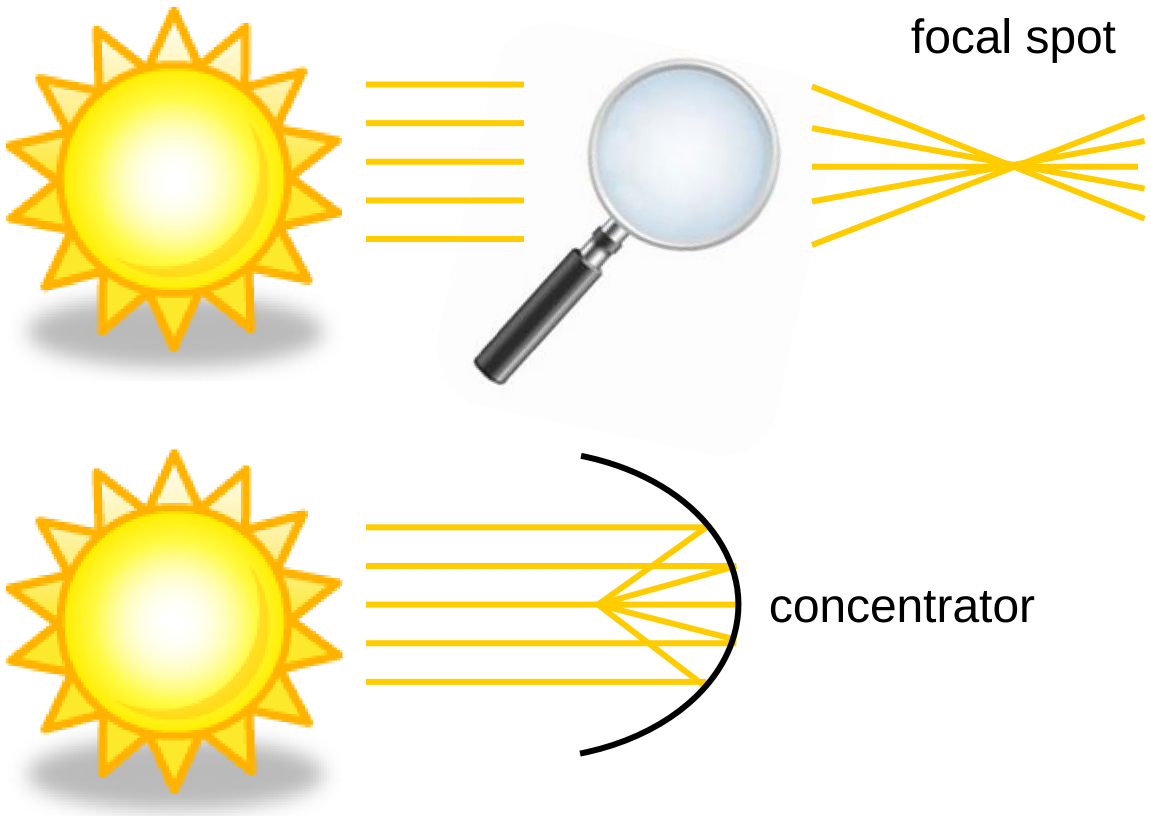
Concentrated Solar Power

Martina Neises-von Puttkamer

Department of Mechanical and Process Engineering, ETH Zurich
8092 Zurich, Switzerland



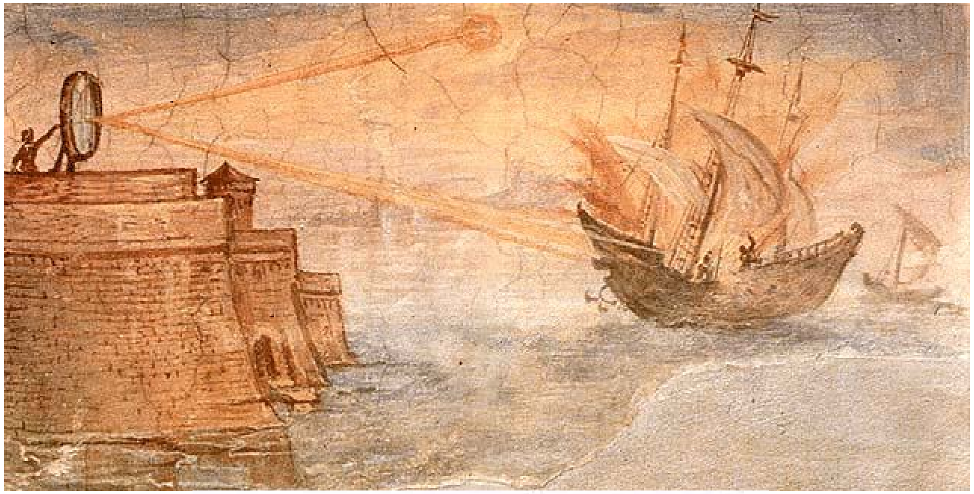
Concentrating solar radiation - Principle



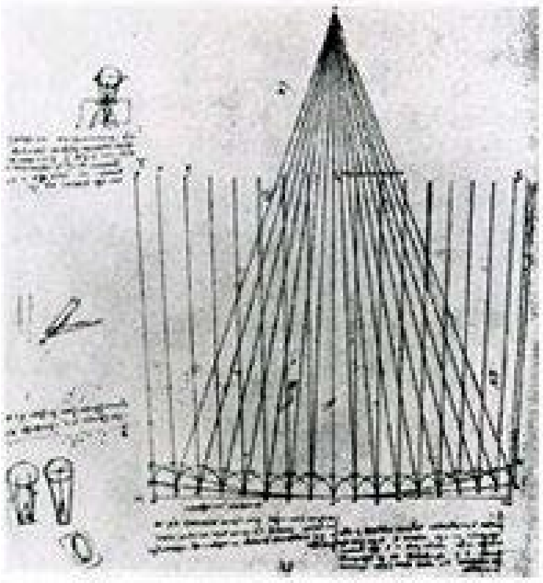
Using solar energy – an old idea recalled to life

- 210 BC: Battle of Syracuse

  Archimedes used mirrors to focus sunlight onto invading ships to set them on fire.

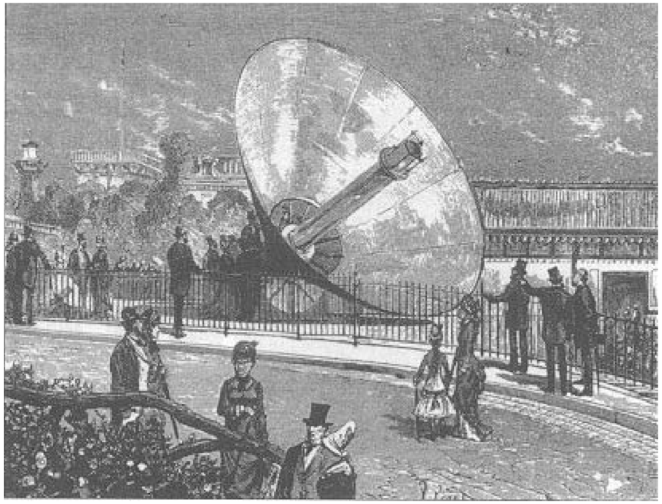


- 1515 : sketches of Leonardo da Vinci show devices for concentrating solar energy



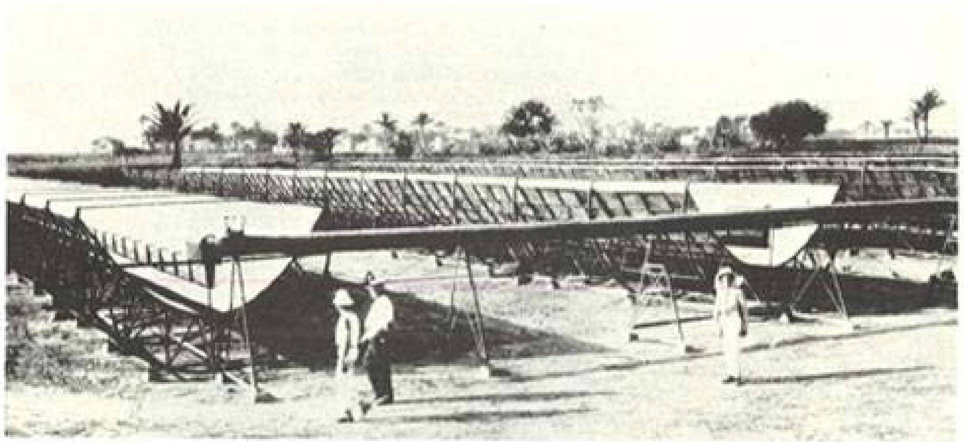
Using solar energy – an old idea recalled to life

- 1878: Augustin Mouchot presented a solar powered steam engine at the Universal Exhibition in Paris.



- 1913: Frank Shuman set up the first solar power station in Egypt

  It generated steam and pumped water from the Nile to adjacent cotton fields.

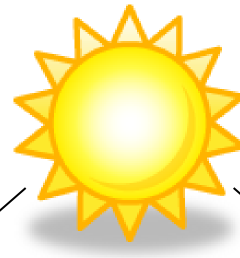


Outline

- Technology
- Electricity generation
- Solar fuels
- Outlook

- Technology
- Electricity generation
- Solar fuels
- Outlook

Types of solar energy converters



energy converter

solar collector
(solar thermal)

- flat plate collector
- concentrating system

solar cell
(photovoltaic cell)

useful energy

heat:
warm water supply
heating

heat:
heating
process heat
electricity

electricity

Solar themal systems

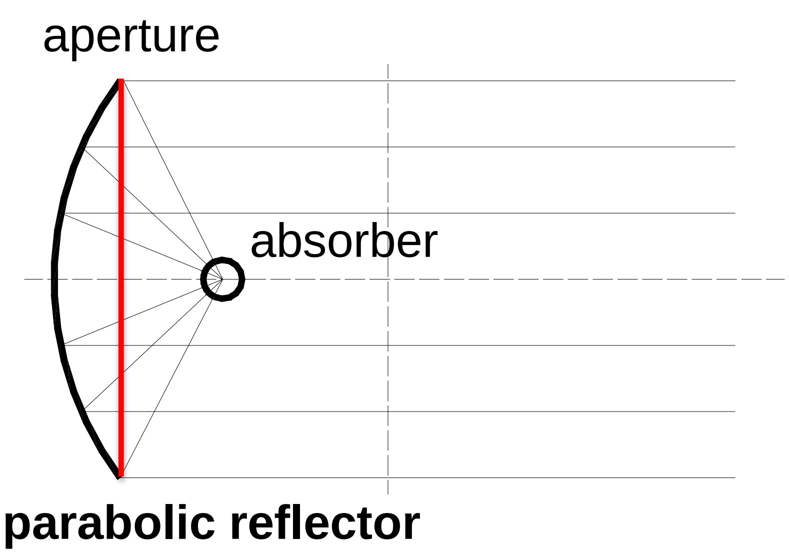
solar thermal systems

high temperature systems

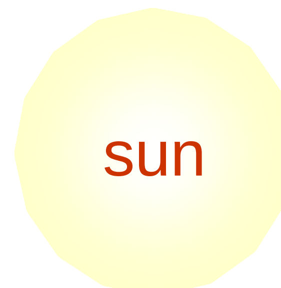
low temperature systems

Concentrating solar irradiation

Solar irradiation is collected over a wide area and focused on a small area



only direct irradiation can
be concentrated



concentration factor

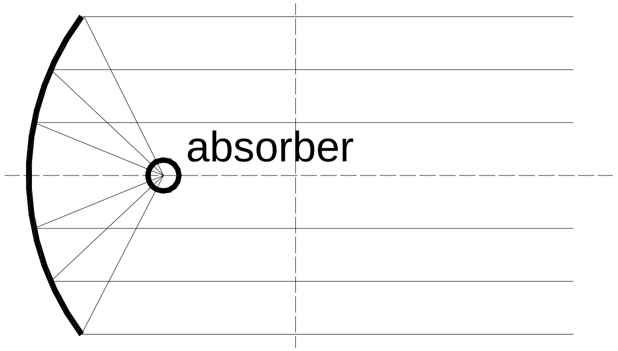
$$C = \frac{\textit{energy density after concentration}}{\textit{energy density before concentration}} = \frac{\textit{aperture area}}{\textit{absorber area}}$$

Maximum concentration factor

- Theoretical maximum: $C_{max} \approx 46200$
- Technical maximum: $C_{max} \approx 5000 - 8000$

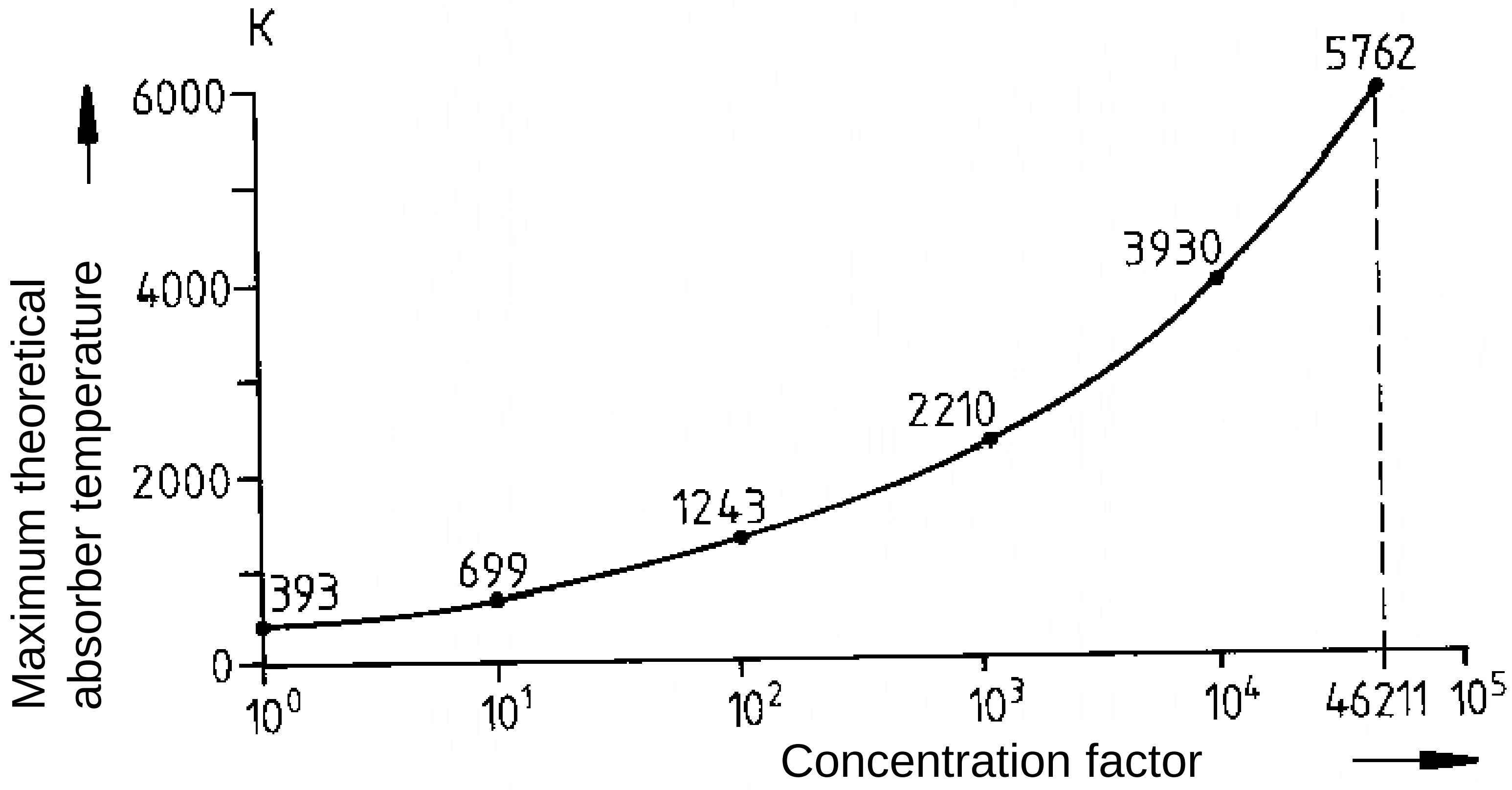
  Due to

  - Imperfect reflection of mirror
  - Surface deformation of mirror
  - Focusing error of mirror
  - Displacement of absorber
  - Imperfect reflection and emission of absorber



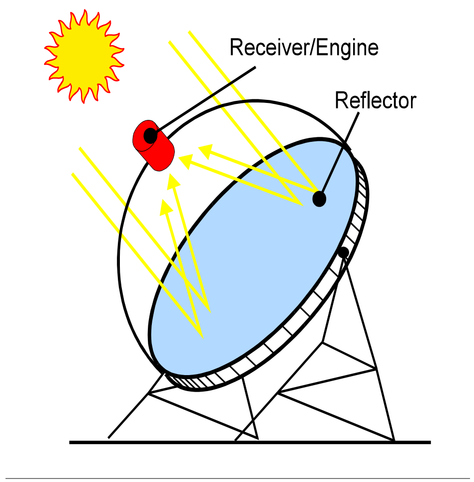
parabolic reflector

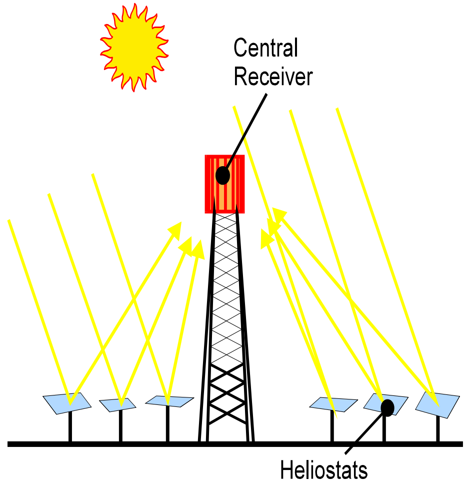
Theoretical maximum absorber temperature

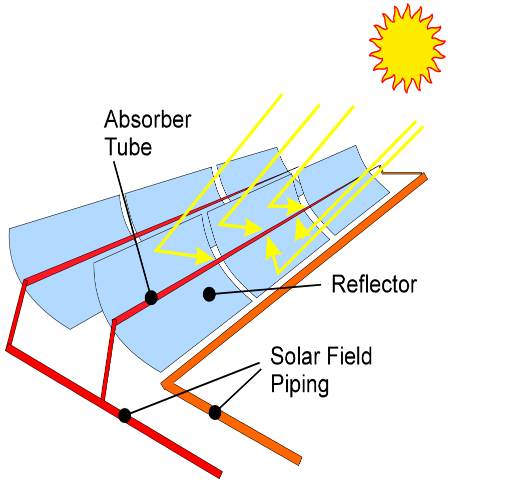


Source: Regenerative Energiequellen, M Kleemann, Meliß

Concentrating systems







dish   solar tower   parabolic trough

point focus or central receiver (3D-conc.)

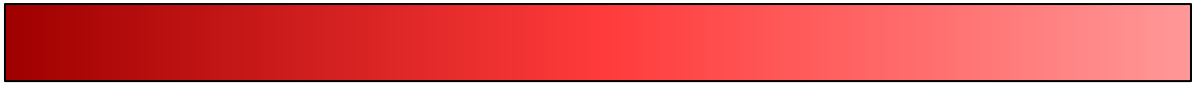
two-axis tracking

concentration 100 - 2000

line focus (2D-conc.)

one-axis tracking

concentration 10 - 100



2000 °C   1000 °C   550 °C

Converting solar energy

Aim: substitution of fossil fuels

Heat

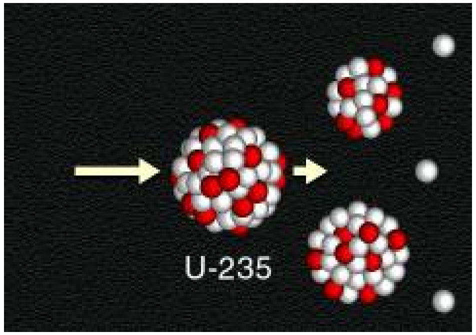
electricity generation
steam turbine
gas turbine
…

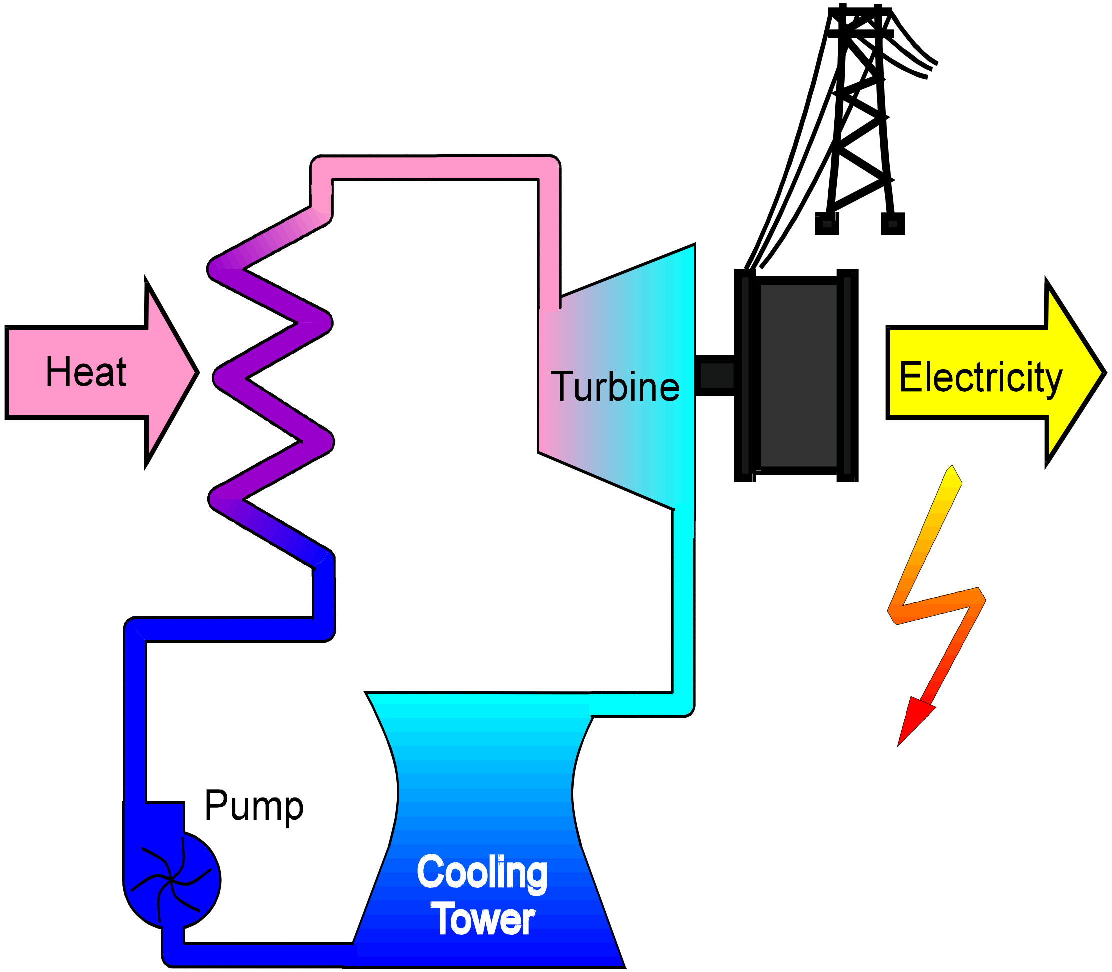
industrial processes
steam
heating + cooling
metals processing
…

solar chemistry
fuel production
e.g. H_2, CH_3OH
…

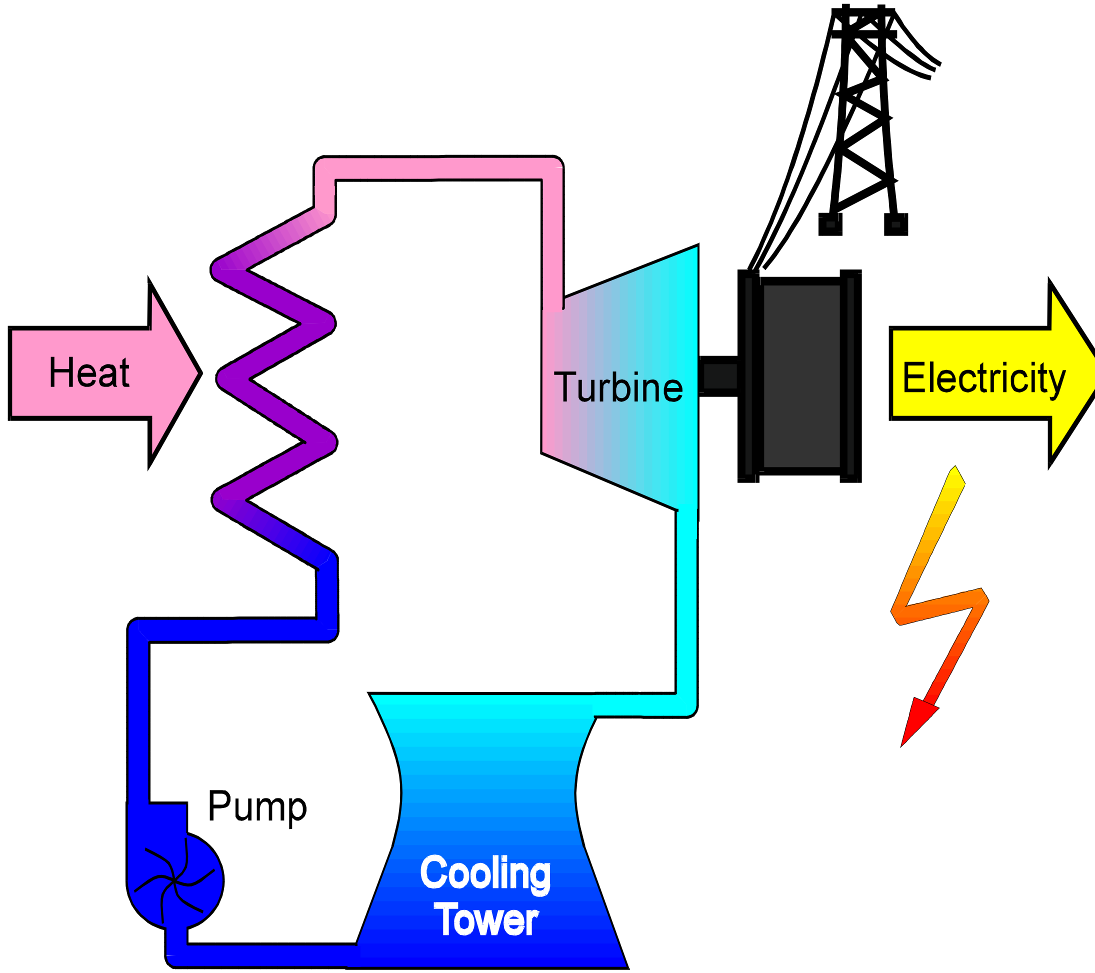
- Technology
- Electricity generation
- Solar fuels
- Outlook

Conventional power plant





Concentrating solar power (CSP) plant



Parabolic trough

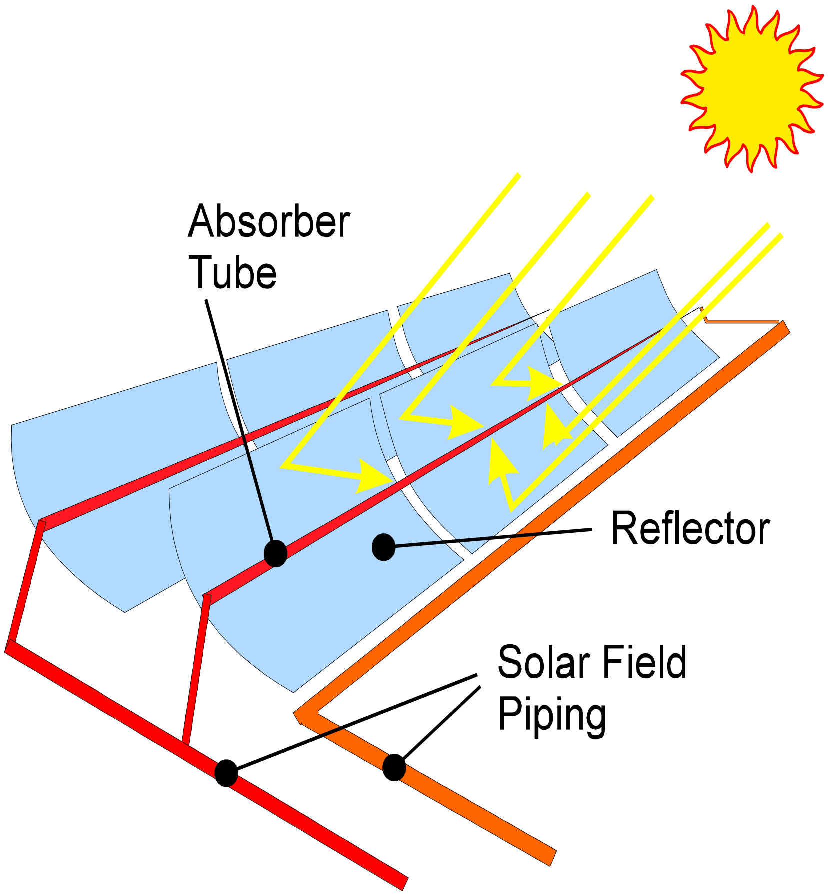
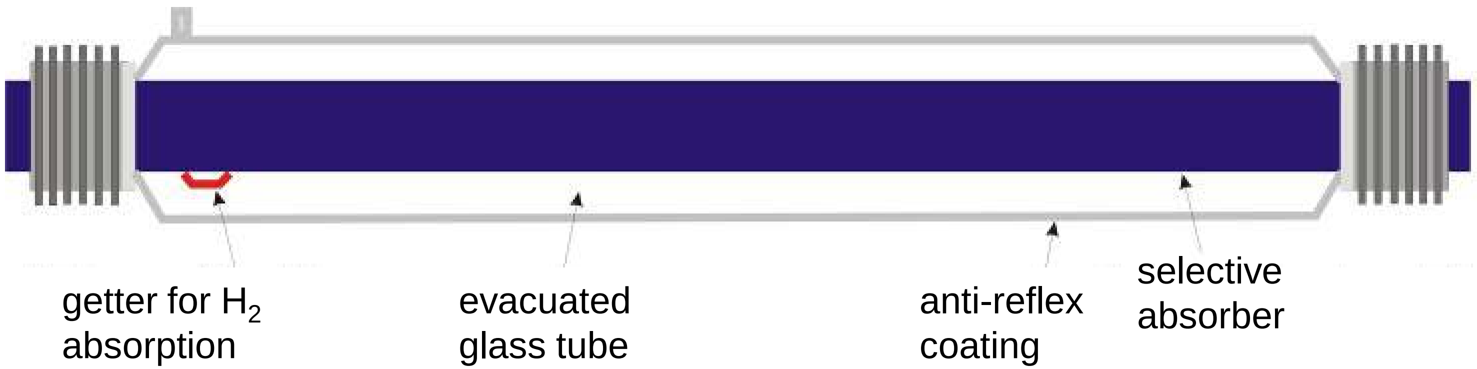


Photo: Flagsol GmbH

$C \approx 100 - 200$, $T = 400 - 550$ °C

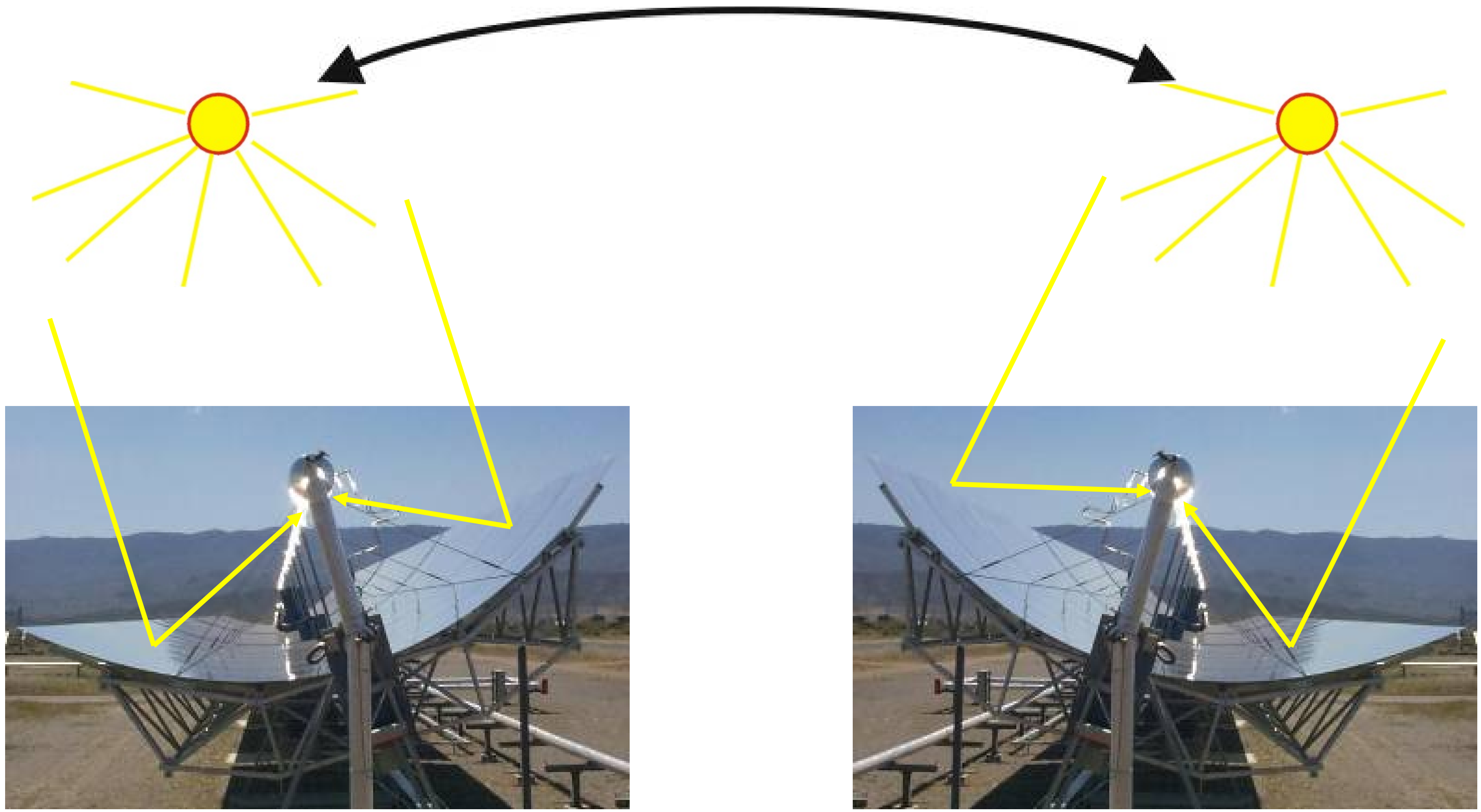
Parabolic trough - receiver



Heat transfer fluid:

- Oil (16 bar / 390 °C)
- Steam (100 bar / 390 – 550 °C)
- Molten salt

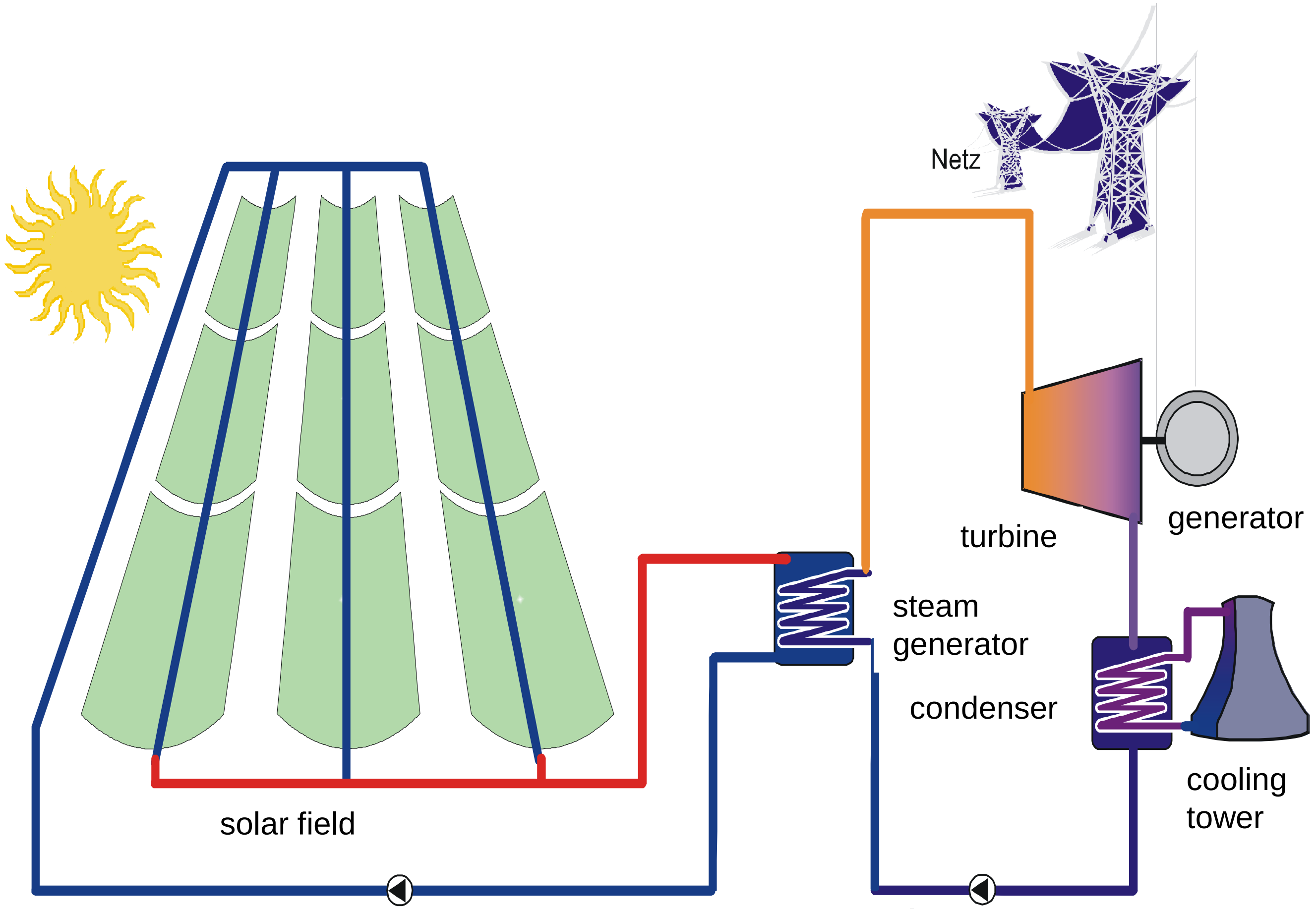
Line focusing system



morning **afternoon**

Parabolic trough power plant

Two closed loops coupled via heat exchanger

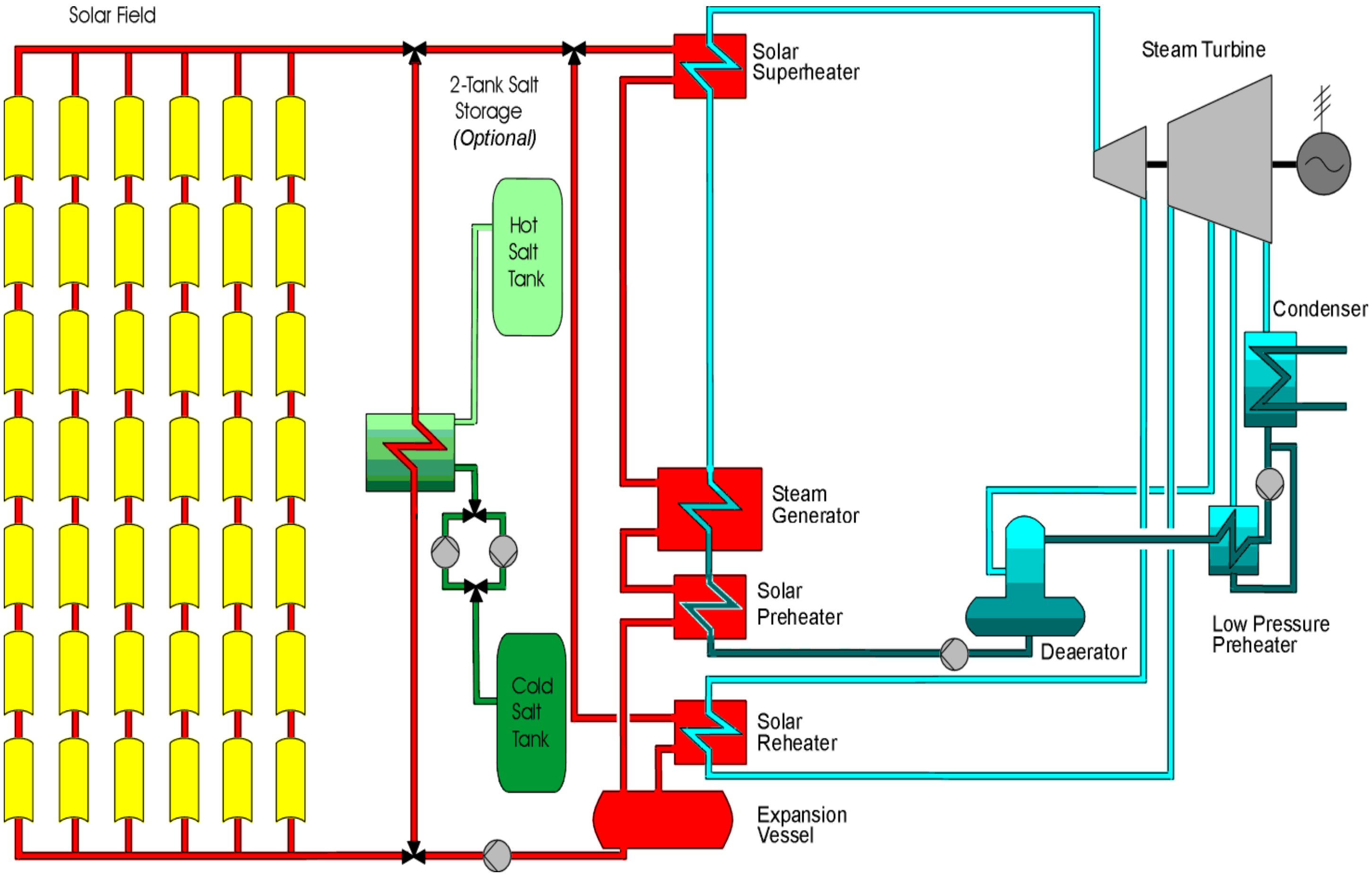


Source: DLR

20

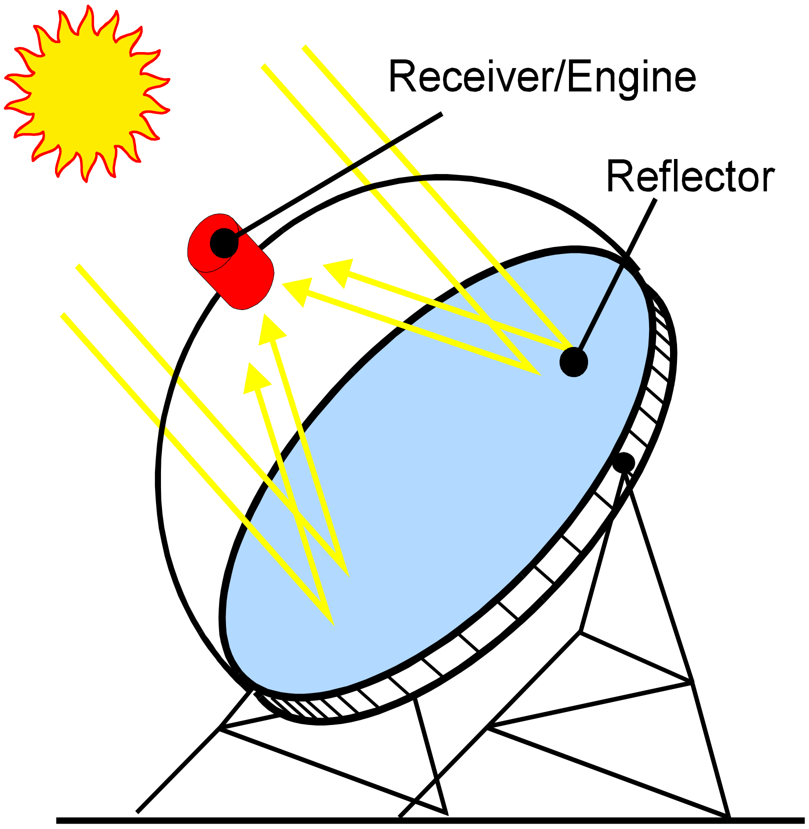
Parabolic trough power plant with storage

solar field storage power block



Source: DLR

Dish



$C \approx 2000$, $T > 2000\ °C$

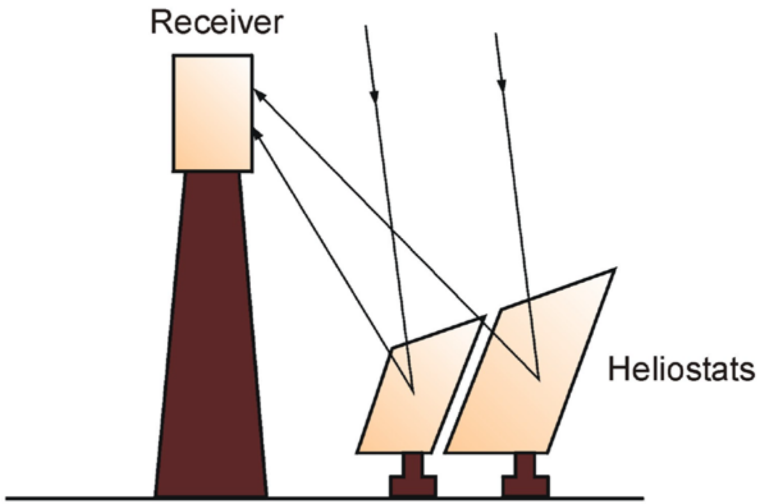
Energy converter:
- stirling motor
- gas turbine

Heat transfer fluid
- air, helium
  (50 - 200 bar / 600 - 1200 °C)

Power of one unit: 10 – 25 kW

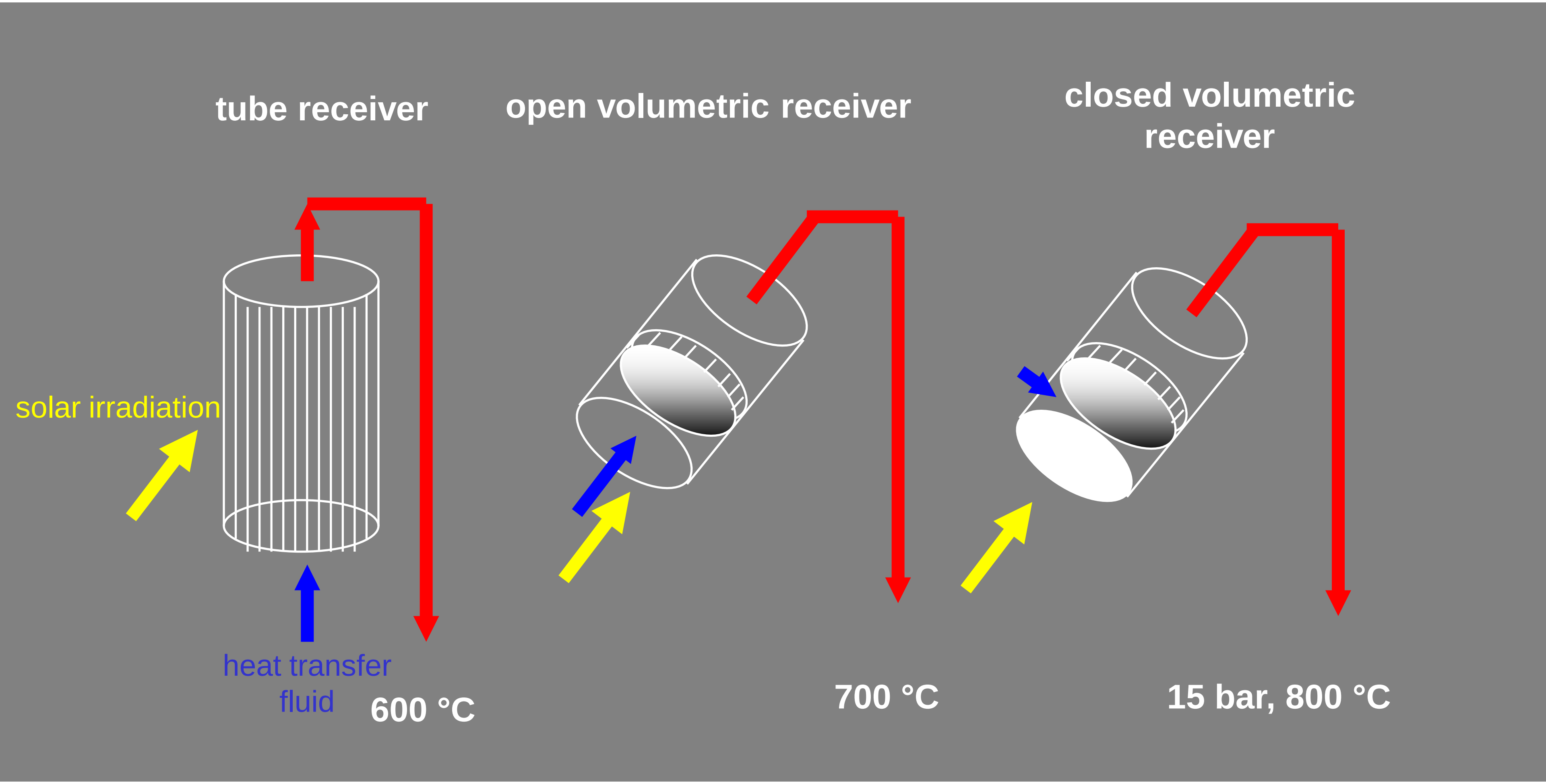
Useful in remote areas

Solar tower



C ≈ 1000, T ≈ 1000 °C

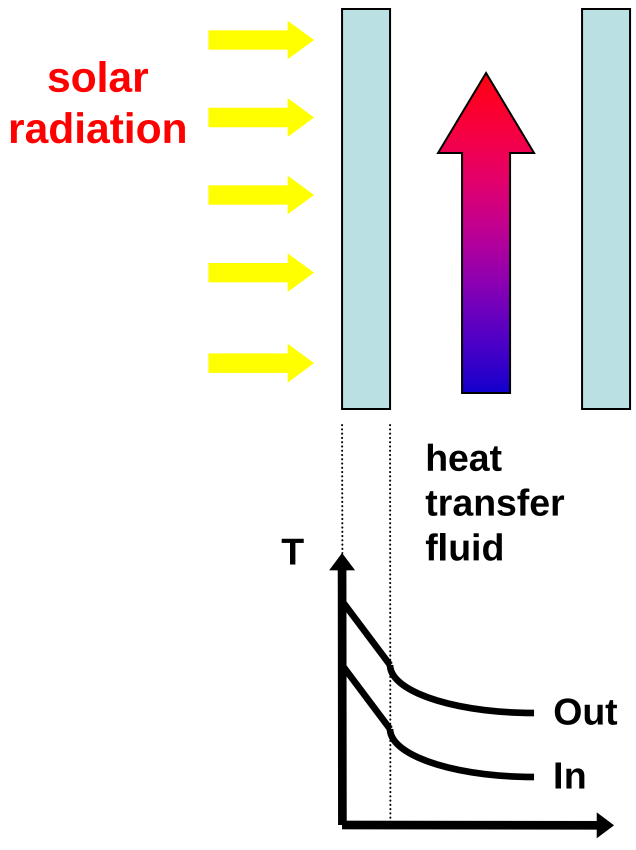
Receiver types



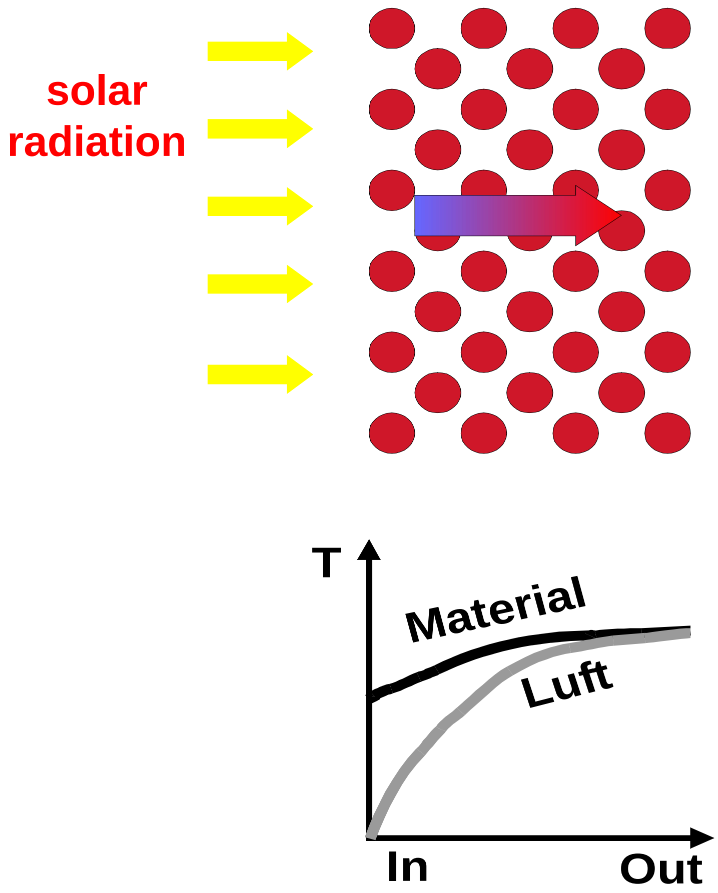
Heat transfer fluid: water/steam, air, molten salt

Receiver types

tube receiver



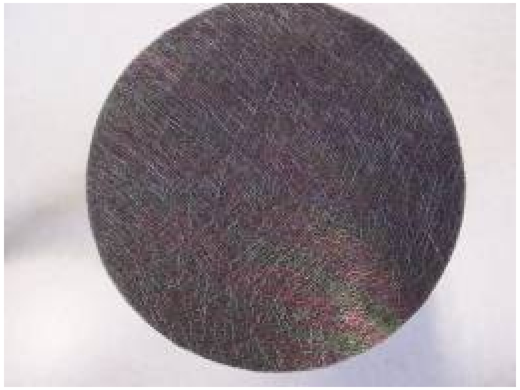
volumetric absorber with air



Volumetric air receivers

wire-meshwork/ felt

metal/ceramic



channel-structure

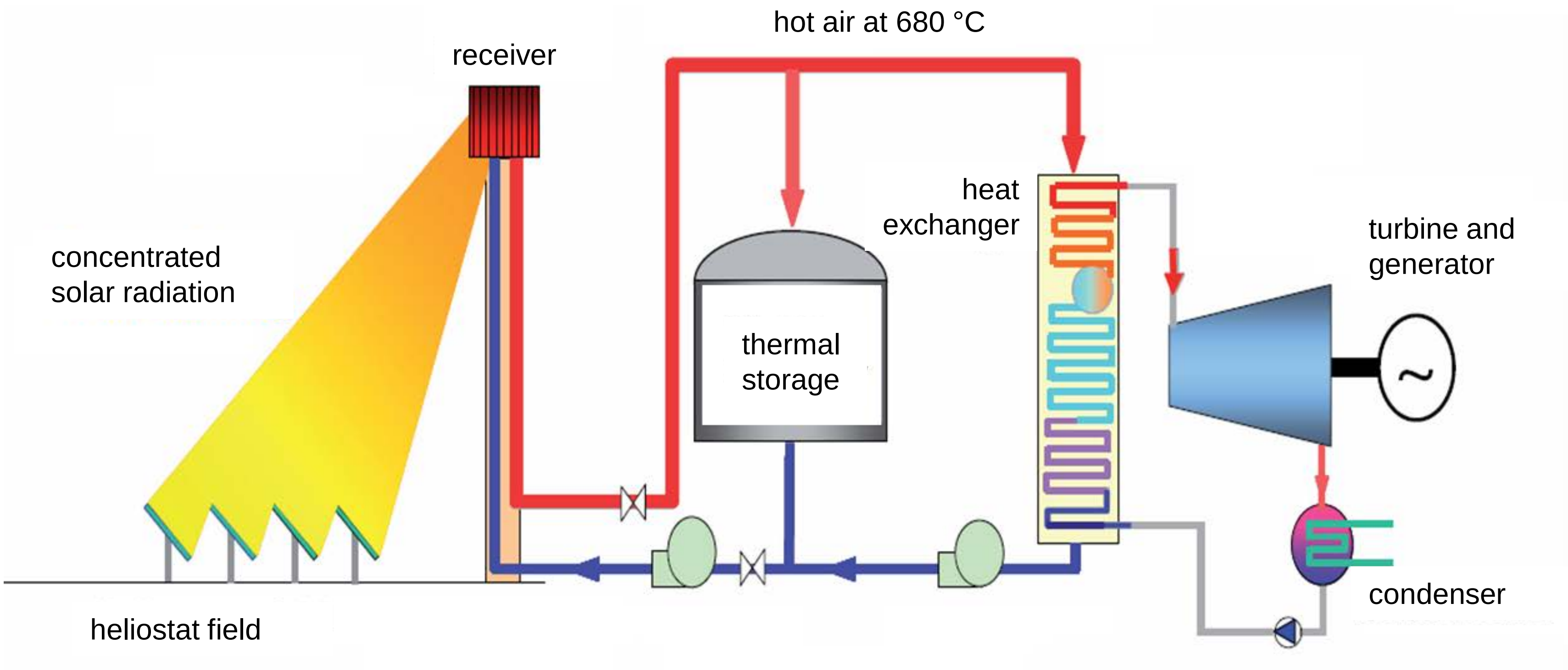
metal

foam

ceramic

Solar tower power plant

with open volumetric air receiver



Source: DLR

Storage – an important component

Thermal Storage for middle to high temperature applications

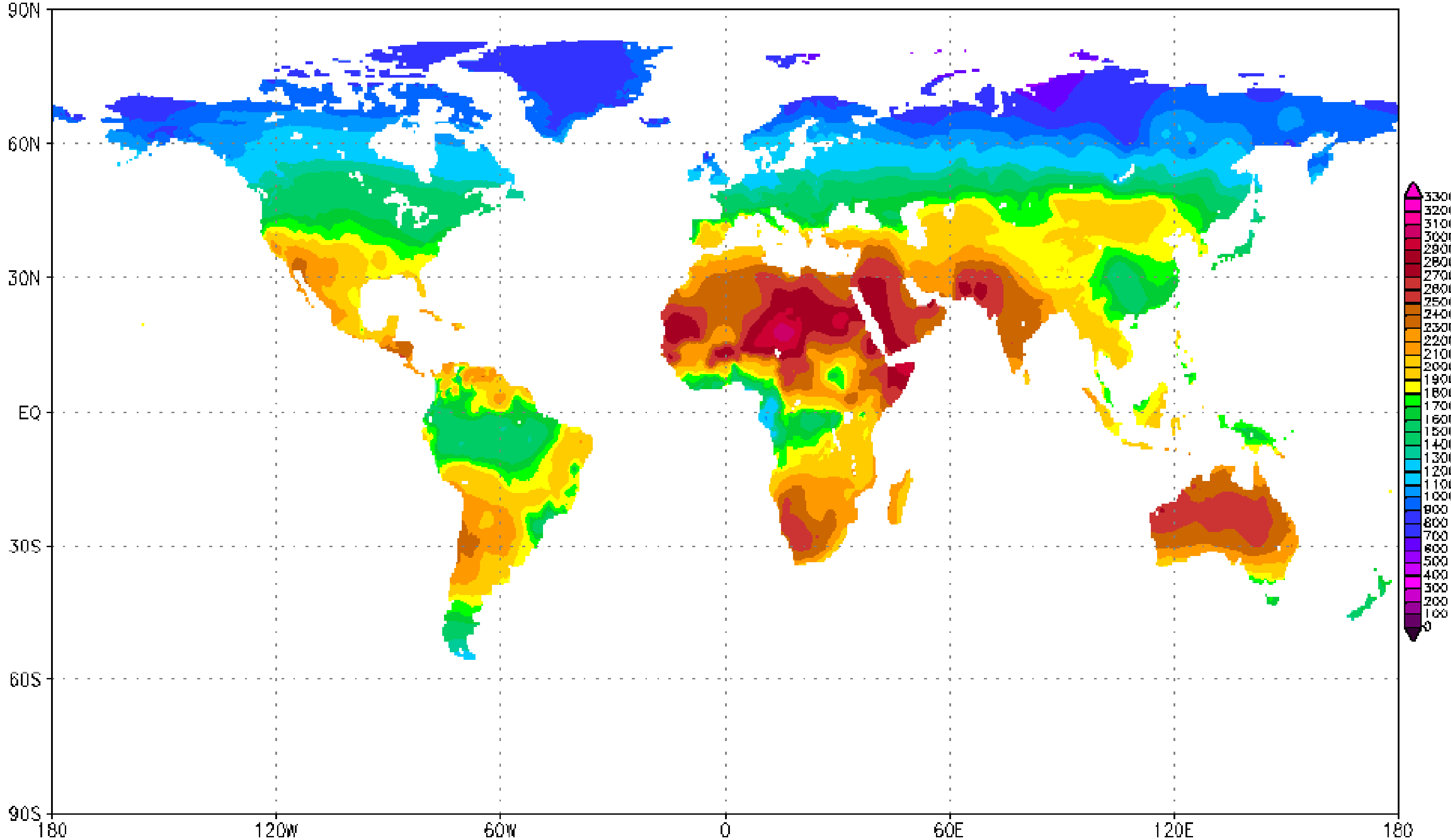
- Sensibe heat storage
  - Direct storage of heat transfer medium (oil, salt)
  - Indirect storage with heat exchanger (salt, concrete, metals, …)
- Latent heat storage
  - With phase change materials (PCM) ($NaNO_3$, KNO_3, …)
- Thermochemical heat storage
  - e.g. dissociation reactions

    $Co_3O_4 \leftrightarrow 3CoO + \frac{1}{2} O_2$

    $CaCO_3 \leftrightarrow CaO + CO_2$

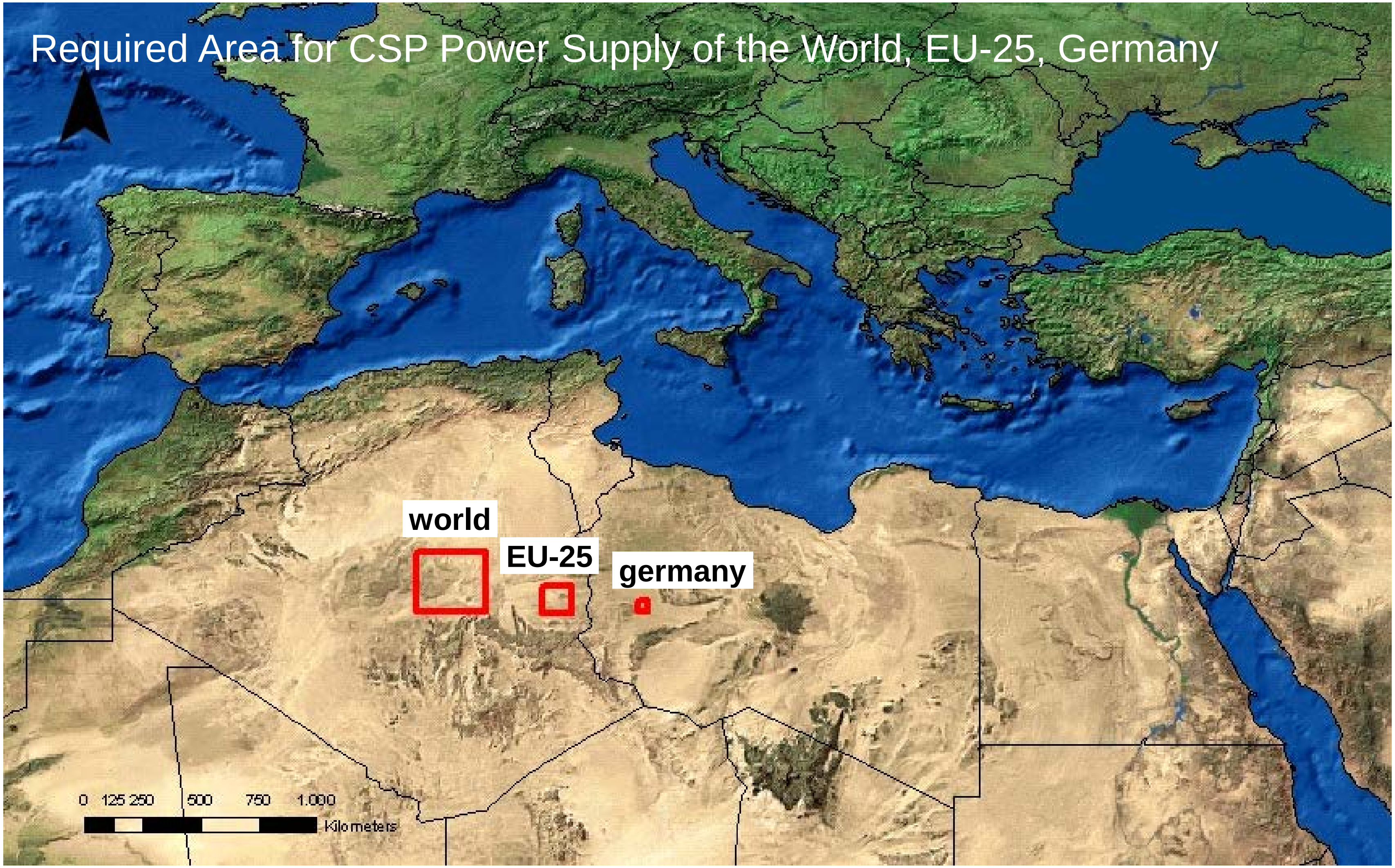
Where is it applicable?

radiation map in kWh/(m²a), global

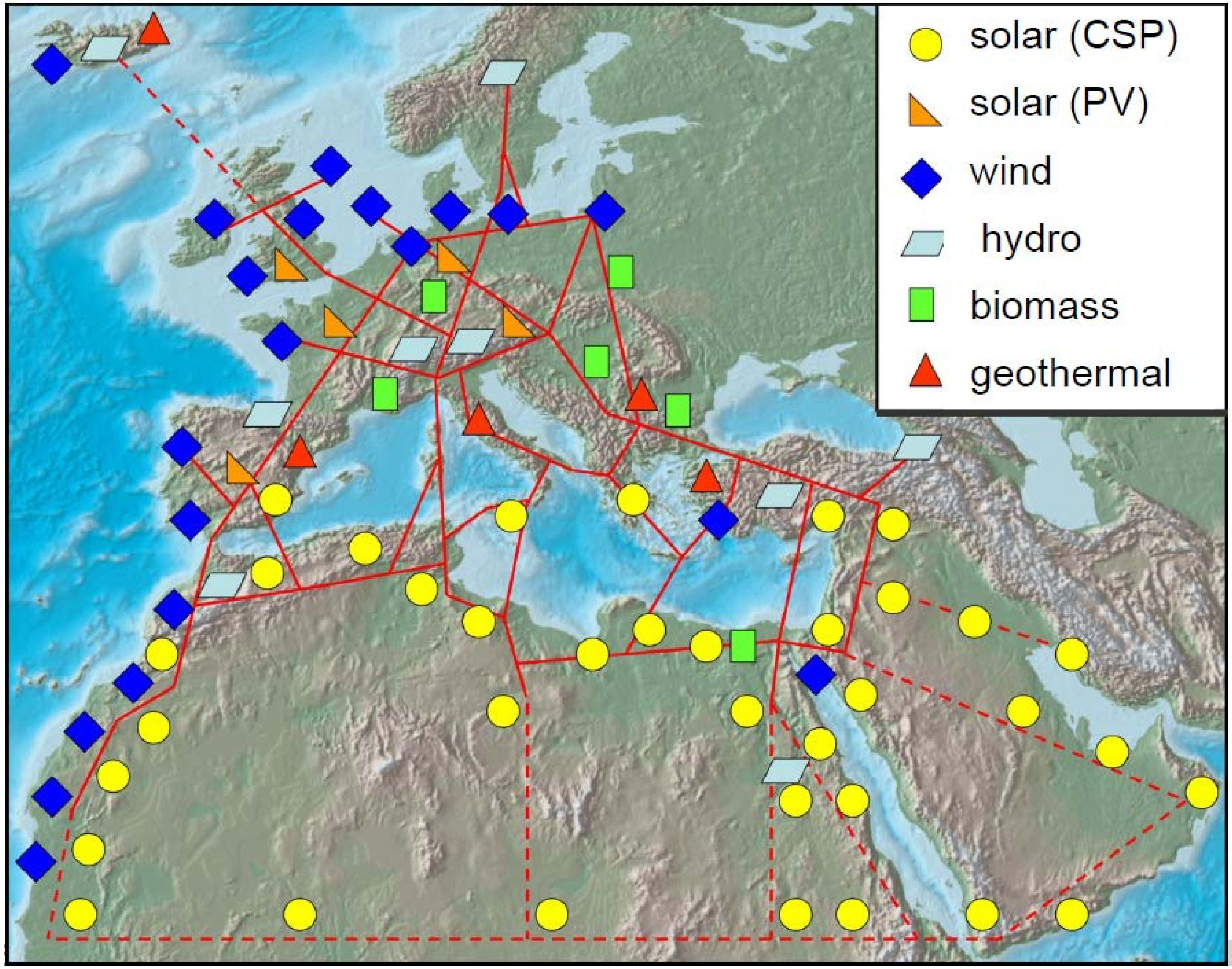


29

What is the potential?



Concept of a renewable energy link between Europe and North Africa



Source: MED-CSP and TRANS-CSP study of DLR, http://www.dlr.de/tt/med-csp and http://www.dlr.de/tt/trans-csp

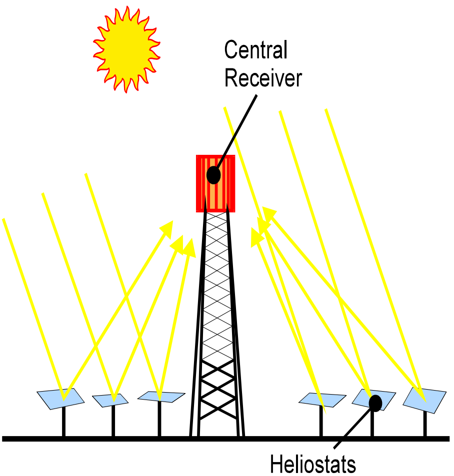
Challenges

- Increase plant efficiency and reduce costs
  - Optics
  - Receiver materials
  - Storage concepts and materials
  - Quality control of manufacturing and mounting process

- Transportation of energy
  - High voltage direct current (HVDC) electric power transmission
  - Energy conversion into fuels

- Technology
- Electricity generation
- Solar fuels
- Outlook

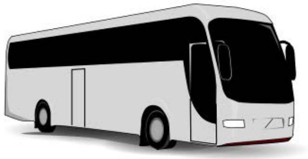
Principle of solar fuel production



Solar Tower

Heat → Chemical Reactor → Fuel: H_2, $CO + H_2$ → Energy Converter: Fuel Cell → Energy Carrier: Natural Gas, Water → Chemical Reactor

Energy Converter → Transportation, Electricity Generation



Transportation

Electricity Generation

Ways of hydrogen production

lean CO_2 — **Fossil fuels** → Reforming, Gasification/PartOx, Cracking

CO_2 neutral — **Biomass** → Pyrolysis

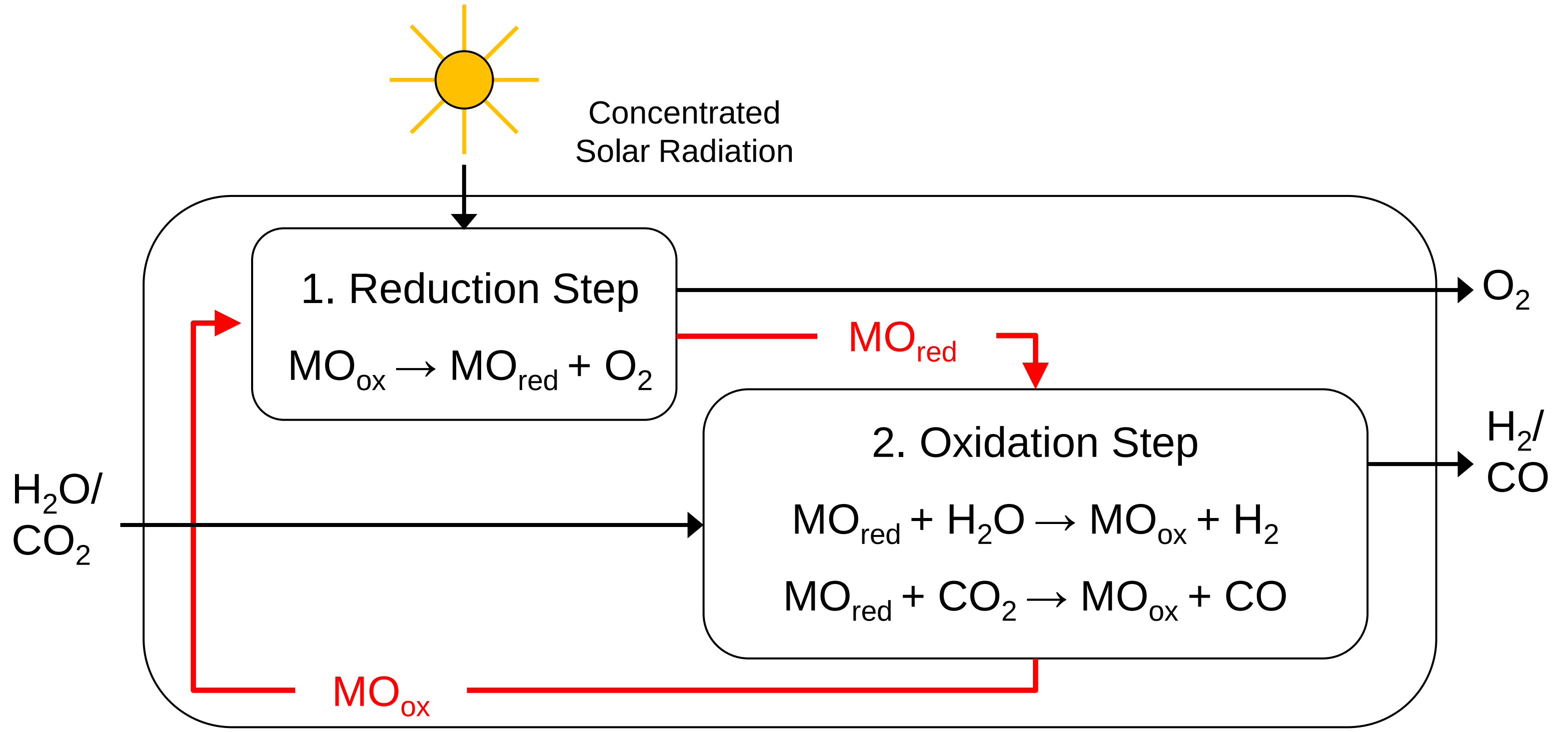
CO_2 free — **Water** → Thermal Splitting, Thermochemical Cylces, Electrolysis

Reforming, Gasification/PartOx, Cracking, Pyrolysis, Thermal Splitting, Thermochemical Cylces: + heat

Electrolysis: + electricity

→ H_2

Two-step solar thermochemical cycle



- No separation of O_2/H_2 necessary
- Temperatures lower than 2000 °C possible
- No intermediate energy conversion step from thermal energy to electricity
- Higher efficiencies compared to electrolysis can be reached

Redox systems: ZnO/Zn, Fe_3O_4/FeO, Ce_2O_3/CeO_2, $NiFe_2O_4$, …

Challenges for future developments

Material

Key issues: Maintenance of high surface area and reduction of temperature

- Reduction of Regeneration Temperature
  - Low oxygen partial pressure through high-purity gases or vacuum
- Maintenance of surface area
  - Stabilization of material through coating or doping …
- Increase reaction rate
  - High surface area and thin surfaces, fast ion conductor
- New Materials
  - e.g. solid solutions of different materials

→ All these points influence the reactor design

Challenges for future developments

Receiver-reactor

Key issues:

- Thermal and chemical efficiency
- Scalability
- Accessible for maintanance or modifications
- Low fault liability

- Reactor concepts will be adapted based on the material developments

- Technology
- Electricity generation
- Solar fuels
- Outlook

- Many possibilities for solar thermal applications
  - Electricity
  - Industrial processes
  - Chemistry

- Future challenges
  - Storage and transportation
  - Efficiency increase
  - Cost reduction

Thank you!